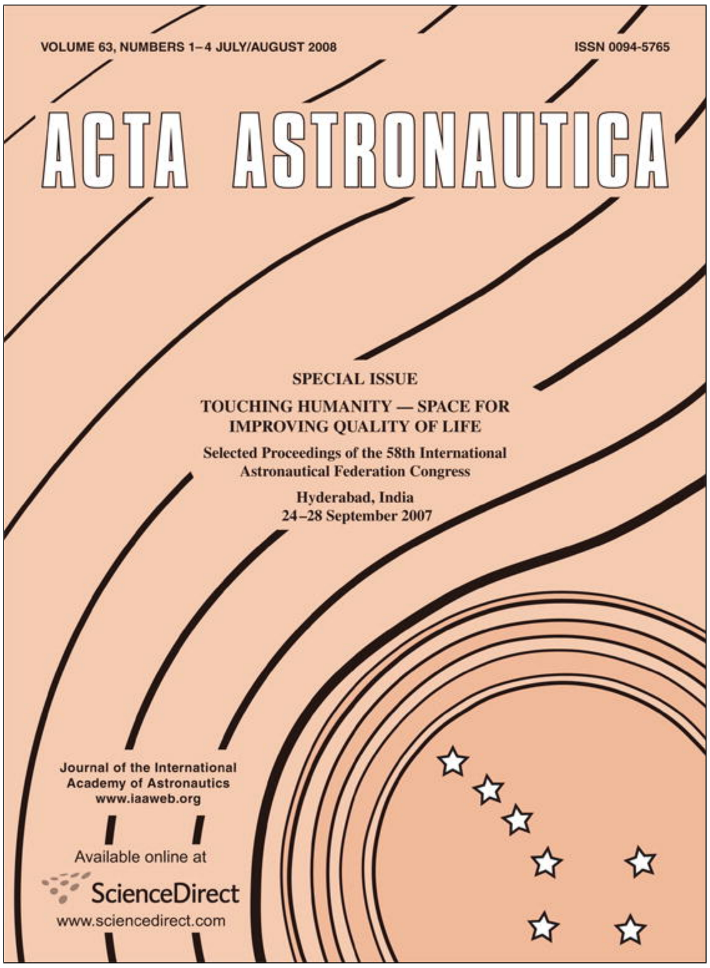
VOLUME 63, NUMBERS 1–4 JULY/AUGUST 2008
ISSN 0094-5765
ACTA ASTRONAUTICA
SPECIAL ISSUE
TOUCHING HUMANITY — SPACE FOR IMPROVING QUALITY OF LIFE
Selected Proceedings of the 58th International Astronautical Federation Congress
Hyderabad, India
24–28 September 2007
Journal of the International Academy of Astronautics
www.iaaweb.org
Available online at
ScienceDirect
www.sciencedirect.com

PERGAMON

Available online at www.sciencedirect.com

ScienceDirect

Acta Astronautica 63 (2008) 285–298

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Extreme environment technologies for NASA's robotic planetary exploration

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Available online 4 March 2008

Abstract

NASA's 2006 Solar System Exploration Roadmap recommended a set of robotic exploration missions for the next 30 years, in small, medium and large mission classes. These proposed missions are expected to target planets, moons and small bodies in the Solar System, while encountering diverse extreme environmental conditions through their mission phases. These extreme environments (EE) include high and low temperatures and pressures, and high radiation environments at various planetary destinations. EE conditions are often coupled, including high temperatures and pressures near the surface of Venus; or low temperatures and radiation at the Jovian System, for instance near Europa. Extreme environments due to mission operations are also a consideration, for example aeroshell thermal heating during planetary entry. While some of the technologies for EE mitigation are currently available, development of numerous new technologies are also required to enable missions and thus NASA's exploration plans. In response, a comprehensive assessment was performed to identify the state of practice for EE technologies. Furthermore, recommendations were given for future technology developments. In this paper we outline the findings of the EE Technologies Study Team, including discussions on the state of practice of EE technologies; mission impacts; and emerging technology capabilities to enable mission architectures. Under emerging technologies we describe protection systems; component hardening for electronics, mechanisms and energy storage under high and low temperature conditions; and mobility operations. It is expected that the recommendations from the EE report would assist NASA with technology program planning and would help identifying priorities for near term technology investments.

1. Introduction

In 2003, the Solar System Exploration Decadal Survey by the National Research Council (NRC DS) [1] recommended that "NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed." The NRC DS report identified the need for a number of technologies for tolerating extreme planetary environments that would be needed to implement a program of high-priority missions. Consequently, a series of studies were undertaken to assess the state of the relevant technologies and to formulate roadmaps to enable NASA's Solar System Exploration (SSE) Program. The findings from these studies are reported in an extreme environments technologies report [2].

Specifically, the information gathered in the studies played a key role in formulating the technology plans included in the Planetary Science Division's (PSD) 2006 Solar System Exploration Roadmap [3]. The Science Mission Directorate (SMD) Science Plan [4]—published in May 2007—also identified technologies for extreme environments, as high-priority systems technologies needed to enable exploration of the outer solar system and Venus.

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doi:10.1016/j.actaastro.2007.12.009

In the SSE Roadmap [3] a number of missions were proposed, which would reach and operate in extreme environments. Environments are defined as "extreme," if they present extremes in pressure, temperature, radiation, and chemical or physical corrosion. In addition, certain planned missions would experience extremes in heat flux and deceleration, leading to their inclusion as missions in need of technologies for extreme environments.

Addressing these technology needs made progress in certain cases, but also had some substantial setbacks. For example, the Aerospace Technology program was dissolved, and its funding was folded into the Exploration Systems Missions Directorate (ESMD). In contrast, some work has been funded by ESMD on components for operation at cold temperatures, and SMD is sponsoring technology development for high-temperature electronics; high-temperature motors; advanced pressure vessels; and thermal control systems as part of NASA's Small Business Innovative Research (SBIR) Program for Robotic Exploration of the Solar System. At this time, however, there is no program within SMD that directly supports development of the needed technologies by NASA centers, universities, and industries not qualifying for the SBIR program.

Therefore, the work summarized here and reported in [2] could play an important role in documenting the need for new technology investments, and in supporting the formulation of a coherent program to address extreme environment technology needs.

2. Planetary missions to extreme environments

In order to prioritize the technology investment areas, it is necessary to understand NASA's planning activities and the mission concepts currently under consideration for planetary exploration.

Within NASA, SMD's primary objective is to implement a set of science-driven strategic and competitive missions. Planning for these missions—which are characterized under three mission classes—can take many years and even decades in advance.

Among these three classes, strategic Flagship class missions are usually directed and larger in their scope, with a projected cost cap between ∼$1.5B and $3B. Smaller Discovery and Scout class, and medium New Frontiers class missions—capped at ∼$425M–$475M and ∼$750M, respectively—are competitive and selected through periodic announcements of opportunity (AO).

Technology planning for large missions is reasonably well defined and the mission impacts are comparatively straightforward to discern. On the other hand, smaller missions are only planned a few opportunities ahead, translating sometimes to five years or less of planning, which introduce limitations to technology development. Therefore, technology development plans for these smaller missions are harder to forecast. SMD missions, both under the Mars Exploration Program (MEP) and the Solar System Exploration (SSE) Program, can be significantly affected by exposure to extreme environments. In addition to these planning efforts, ESMD is developing plans for robotic and manned missions to the Moon and subsequently to Mars. These ESMD plans are still in a formulation phase, and were not considered in this study in detail.

As discussed in NASA's 2006 SSE Roadmap, among the Flagship class missions the Europa Explorer (EE) is the leading candidate for the first Flagship class mission, with an earliest launch date of 2015. Second decade missions would include the Titan Explorer and the long-lived Venus Mobile Explorer (VME). For the third decade, the options could be influenced by the findings of the Europa Explorer mission, leading to a selection between the Neptune/Triton Explorer or a Europa Astrobiology Lander (EAL).

The initial New Frontiers class missions included the 2006 New Horizons Pluto-Kuiper Belt mission (launched in January 2006), and Juno (a Jupiter Polar Orbiter mission without probes), planned for a 2011 launch. Potential New Frontiers missions for the 2015 opportunity include concepts for: Comet Surface Sample Return (CSSR), Lunar South Pole Aiken Basin Sample Return, Venus In Situ Explorer (short-lived), or Saturn Flyby with Shallow Probes (SFSP).

In order to understand the timeline of technology investment, mission concepts were then grouped by extreme environment, but sorted by launch date, rather than mission phase. Technology readiness dates were also calculated, assuming a six-year lead time for Flagship missions and five years for New Frontiers. This analysis is shown in Table 1.

Some of the missions shown in Table 1 target planetary destinations with harsh conditions, while others will go to environments similar to those explored over the past 40 years. Specifically, Mars orbiter and planetary flyby missions would not require significant technology development because the spacecraft environment is well understood and well controlled. Other missions, however, may require significant technology development.

Table 1
Proposed missions to extreme environments until 2035

Mission	Class	Earliest launch date	Projected technology readiness date
High temperatures and pressures			
Venus In Situ Explorer (VISE)	NF	2015	2010
Venus Mobile Explorer (VME)	Flagship	2025	2019
Saturn Flyby with Shallow Probes (SFSP)	NF	2015	2010
Jupiter Flyby with Deep Entry Probes (JDEP)	NF	2020	2010
Low temperatures			
Lunar South Pole Aiken Basin Sample Return	NF	2015	2010
ESMD Lunar Surface Missions	TBD	2011+	2007
Comet Surface Sample Return (CSSR)	NF	2015	2010
Titan Explorer	Flagship	2020	2014
Neptune/Triton Explorer	Flagship	2030 – TBD	2024
Low temperatures and high radiation			
Europa Explorer (EE)	Flagship	2015+	2010
Europa Astrobiology Lander (EAL)	Flagship	2030 – TBD	2024

3. Extreme environments

For the purposes of this assessment, a mission environment is defined as "extreme" if one or more of the following criteria are met: (a) *heat flux at atmospheric entry* exceeding $1\,\mathrm{kW/cm^2}$; (b) *hypervelocity impact* higher than 20 km/s; (c) *low temperature*: lower than $-55\,°\mathrm{C}$; (d) *high temperature*: exceeding $+125\,°\mathrm{C}$; (e) *thermal cycling*: between temperature extremes outside of the military standard range of -55 to $+125\,°\mathrm{C}$; (f) *high pressures*: exceeding 20 bars; (g) *high radiation*: with total ionizing dose (TID) exceeding 300 krad (Si). Additional extremes include (h) deceleration (g-loading) exceeding 100 g, (i) acidic environments; and (j) dusty environments.

A summary of targets of interest and the relevant extreme environments are shown in Table 2. Targets are organized by extremes in temperature; however, it is evident that missions often encounter multiple extremes simultaneously. In general, high temperature and pressure are coupled and typical for Venus in situ and deep entry probe missions to giant planets, such as to Jupiter and Saturn. High radiation and low temperature are also coupled for missions to the Jovian system; relevant mission concepts are the Jupiter orbiter and Europa lander missions. Low-temperature missions are associated with surface missions to the Moon, Mars, Titan, Triton, and comets. Thermal cycling with fluctuations of 60–100 °C would affect missions where the frequency of the diurnal cycle is relatively short, such as for Mars (similar cycle to Earth) and on the Moon, where the day length is 28 Earth days.

4. State of practice for EE technologies

During more than 40 years of planetary exploration, a variety of architectural approaches and technological solutions have been used to cope with these extreme environments. A brief overview of these are given below.

4.1. Hypervelocity impact environments

These environments are ubiquitous in Earth orbit and interplanetary space, but for planetary missions the greatest challenges have occurred in the exploration of active comets (where the density of coma particles far exceeds the space ambient), and in crossing Saturn's ring plane. Three NASA Discovery-class missions to active comets—Stardust, CONTOUR, and Deep Impact—were all equipped with shielding to cope with the environment. Stardust and CONTOUR used multilayer Whipple shields composed of a multilayer Nextel "bumper" to disrupt particles and included a Kevlar backup layer. The Deep Impact mission, which consisted of two spacecraft, employed the most complex approach to protection because of the need to observe the comet throughout the comet encounter.

The Flagship-class Cassini mission protected vulnerable parts of its vital propulsion system from the low-level, but still mission-threatening, ambient micrometeoroids flux during its long cruise phase by exploiting the particle disruptive properties of multilayer insulation (MLI). Especially vulnerable components such as the rocket nozzles are protected with a retractable cover that is withdrawn when the engines are

Table 2
Extreme environments in the Solar System

Target	Radiation (krad/day)	Heat flux at atm. entry (kW/cm^2)	Deceleration (g)	Pressure (bar)	Low temperatures (°C)	High temperatures (°C)	Rotational period (Earth days)	Chemical corrosion	Physical corrosion
High temperatures									
Venus		2.5	300	92		482	243	Sulfuric acid clouds	
Jupiter (upper atmosphere)		30	228	22		230	0.4		
Low temperatures									
Lunar permanently shadowed regions					−230				Dust
Comet (nucleus)		0.5[a]			−270				
Titan		0.01	15	1.5	−178		16	CH_4	
Enceladus (equator)					−193				
Enceladus (south pole)					−188				
Low temperatures and high radiation									
Europa (orbit)	40								
Europa (surface)	20				−180		3.6		
Europa (sub-surface)	0.3 at 10 cm				∼0 at 5 km				
Thermal cycling									
Moon					−233	+197	27		Dust
Mars		0.05–0.1		0.007	−143	+27	1		Dust

operated. For the much more intense, but highly directional fluxes experienced in crossing the narrow ring plane, the spacecraft must be oriented in the least vulnerable attitude.

4.2. Hypervelocity entry environments

Entry environments experienced in planetary missions range from the comparatively benign environments at Mars and Titan, to the more severe environments at Venus and Earth (required for sample return), to the most severe environments at the giant outer planets. The Galileo entry probe entered the atmosphere of Jupiter at more than 47 km/s, more than four times the entry velocity of the Pioneer Venus probes. The Galileo probe used a deceleration module of a similar design to the Pioneer Venus probes and its ablative heat shields were protected with dense carbon phenolic material. Sensors in the heat shield indicated that more than half the mass of the heat shield and almost one quarter of the mass of the entire probe was ablated during entry. In terms of future missions to Jupiter and other giant outer planets, there is a concern that it will be difficult to replicate the carbon phenolic technology and to validate it, because NASA's hydrogen arc jet facility is no longer operational and would be very costly to refurbish.

4.3. High-pressure and high-temperature environments

These environments have been experienced by Soviet and US missions to the deep atmosphere and surface of Venus. The Soviets sent their first probe into Venus before the severity of the surface conditions was known, but by the time of the last mission they had developed the technology for surviving, making measurements in the surface environment, and acquiring samples within the constraints of a mission limited to 2 h of surface time. They also appear to have developed methods for coping with the corrosive aspects of the environment—not only for sulfuric acid in the upper atmosphere (using Teflon-coated VEGA balloons), but also carbon dioxide in a supercritical state in the lower atmosphere.

Pioneer Venus, NASA's only mission to the deep atmosphere of Venus, was purely an atmospheric probe not designed or equipped for surface observations. Unlike the Soviet probes, Pioneer Venus probes were only tested in a nitrogen environment at the temperature and pressure conditions of the Venus surface. A number of spacecraft anomalies experienced by both the Pioneer Venus probes and the early Soviet spacecraft as they descended towards the surface of Venus. These anomalies may be attributable to the transition of the atmosphere to supercritical CO_2.

4.4. Cold-temperature environments

Severe cold-temperature environments are inherent to exploration of the outer solar system and are experienced in the inner solar system during the exploration of airless bodies (Moon, Mercury, asteroids) and Mars, a body with a thin atmosphere and extreme diurnal temperature changes. Short-duration missions, such as the Huygens probe to Titan, have coped with environments as cold as 90 K. The Mars Exploration Rover (MER) mission, a multiyear mission, experiences diurnal temperature cycles with lows near 170 K and protects electronic components that will not function over this range in a warm electronics box (WEB). The MER rovers used a lithium-ion battery with an advanced electrolyte, permitting operation down to −40 °C.

4.5. Severe radiation environments

While ionizing radiation environments are ubiquitous in space, the focus of this report is on the most severe environments, which are encountered in the radiation belts of Jupiter. In its multiyear mission, the Galileo orbiter not only provided the most complete characterization of this environment, but was exposed to a much higher cumulative dose of 600 krad—higher than any other planetary spacecraft—before the mission was ended by sending the spacecraft to impact Jupiter. To cope with the Jovian environment, Galileo employed extensive use of shielding, radiation-tolerant electronic parts, and operational methods for recovering from radiation damage. The extensive base of experience from Galileo on the nature of the Jovian environment, its effects on spacecraft components, and methods of mitigating these effects is being applied to the Juno (Jupiter Orbiter) mission currently in formulation and to other missions that are in the study phase.

5. Mission impact of EE technologies

The mission set used to evaluate developments in extreme environment technologies is based on the recommendations of the NRC DS [1]. In 2005, NASA's PSD assembled a set of Design Reference Missions, based on the NRC DS recommendations, which were used to formulate a three-decade strategy in the 2006 Solar System Exploration Roadmap [3]. Inputs from this study on the technology readiness were used in determining the sequence of missions in the Roadmap. The first decade of Roadmap missions has been adopted in the SMD Science Plan, published in March 2007 [4]. The extreme environments that will be experienced by these future missions are depicted in Table 2.

5.1. Hypervelocity impact

All long-duration missions in the solar system are subject to a hypervelocity impact hazard, but among the roadmapped missions a return to the Saturn system is likely to involve the most difficult challenges. Cassini's ability to penetrate Saturn's rings and to conduct a close-up reconnaissance of the plumes of Enceladus is limited by the design of the spacecraft. Advances in shield technology might enable more aggressive sampling of the icy plumes in a future mission to Enceladus.

5.2. Hypervelocity entry

Although the NRC DS recommended development of entry probe technology that could enable entry into Jupiter's atmosphere, NASA selected a mission in 2006 that probes Jupiter's atmosphere with remote sensing and therefore did not require entry probe technology. In 2006, the Solar System Exploration Roadmap recommended a Saturn entry probe mission for which the entry velocity ($\sim 26\,\mathrm{km/s}$) is much smaller than for Jupiter ($\sim 47\,\mathrm{km/s}$) and correspondingly less technically challenging. While probe missions to Uranus or Neptune may be even less technically challenging than for Saturn, orbital missions to these distant targets may require aerocapture technology. Aerocapture requires extended hypervelocity sustained flight through the atmosphere, placing new demands on the performance of the thermal protection system (TPS) and requiring other new technologies as well, in connection with guidance, navigation and control, and thermal management.

5.3. High temperatures and high pressures

Prior landed missions to Venus have been limited to surface lifetimes up to two hours. The proposed Venus In Situ Explorer (VISE) mission, which will investigate surface chemistry at one location on Venus, would be enhanced by passive technologies (advanced pressure vessels, insulation, phase-change materials) that extend Venus surface mission lifetime. These technologies would also be applicable to deep probe missions to Jupiter, Saturn, and other outer planets. Missions such as the VME, which are planned to operate at the surface of Venus for several months, will also require internal power generation, coupled with active cooling technologies, and high-temperature electronics to achieve the long-lifetime objectives. Sample acquisition mechanisms will necessarily be exposed to the environment and advances in components would have major advantages.

5.4. Low temperatures

While all missions to the outer solar system are exposed to cold temperatures, in situ missions present the greatest challenges because of their power constraints and thermal control complexities. Low-temperature batteries and low-temperature electronics can enable extended operations on cold targets. For mobile vehicles with motors and actuators exposed to the surface environment, cold electronics can greatly simplify cabling.

Repetitive changes in environmental conditions can cause even more stress on engineering systems than stable extreme conditions. Slowly rotating bodies such as the Moon and Mercury experience extreme temperature excursions between night and day, thus electronics and components must be designed to tolerate the resulting cyclical stresses.

5.5. Ionizing radiation

The highest priority mission recommended by the Decadal Survey is Europa Explorer (EE)—a mission to orbit the Jovian satellite Europa. A typical mission profile of two years in Jupiter orbit followed by a 90-day mission in Europa orbit will involve radiation doses five to ten times that experienced by the Galileo mission. The EAL, conceived as a follow-on mission to EE, may experience lower dose rates than the orbiter, due to Europa's self-shielding. However, lander missions are much more mass constrained than orbiters, so it is possible that the requirements on the components might be even more demanding.

6. Systems architectures to mitigate extreme environments

Systems architectures for extreme environments can be categorized by: the isolation of sensitive materials from hazardous conditions; the development of sensitive materials, tolerant to hazardous conditions; and an appropriate combinations of isolation and tolerance.

6.1. Environmental isolation

One potential solution for extreme environment system architectures is to maintain all electronics and

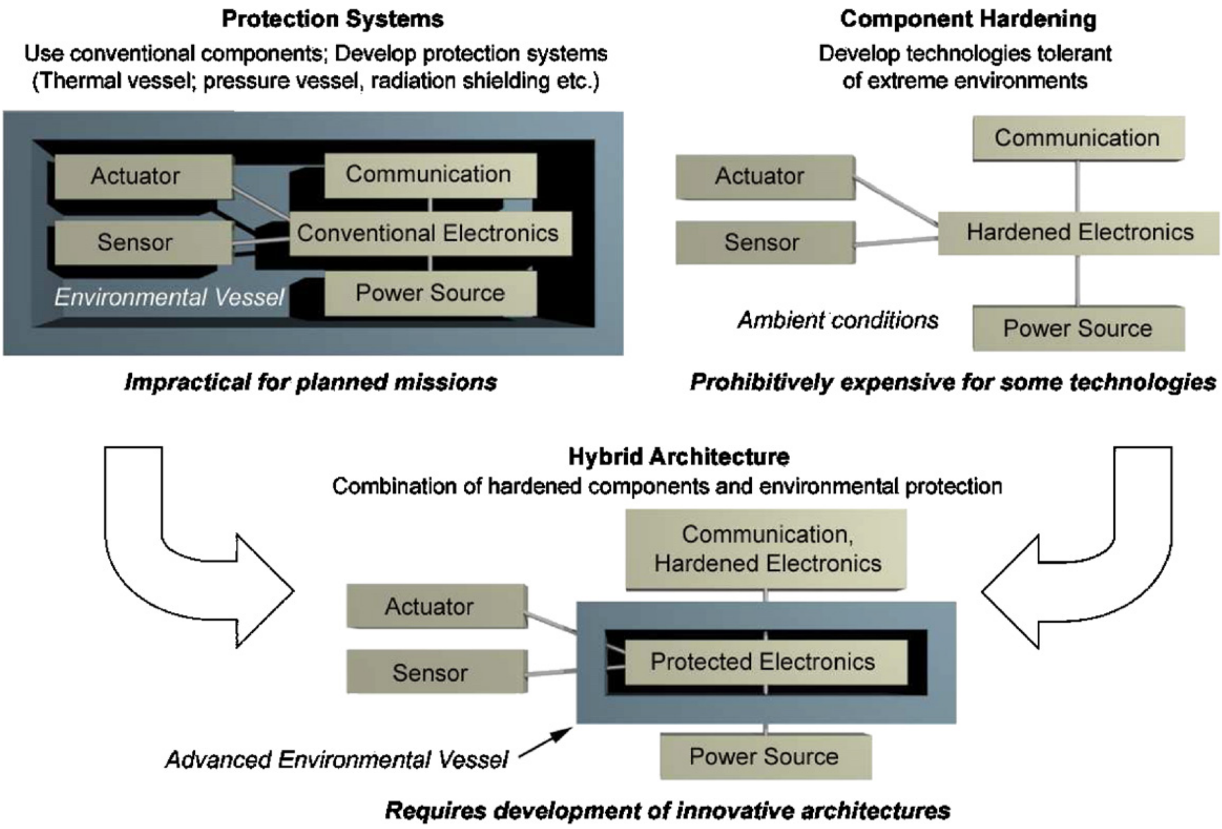

Fig. 1. Illustration of the pressure vessel and thermal management for a Venus in situ mission.

sensitive components in an environmentally controlled vessel (see Fig. 1). While this could be a feasible option, its implementation could have a significant impact on cost and even on the overall mission architecture. Consequently, environmental isolation architectures typically require additional resources, thus, they may not provide ideal solutions for all missions to extreme environments. In addition, some of the in situ components—e.g., sensors and sample acquisition systems—would be directly exposed to the environment, making the implementation of this approach even more challenging.

6.2. Environmental tolerance

An alternative extreme to isolation is the development of hardware components that could reliably operate and survive in extreme temperature/pressure conditions or radiation (see Fig. 1). This would eliminate the need for environmental control, however, this approach is considered ideal only on the purely theoretical level, since some of the key technologies would require a large investment to achieve the desired performance (e.g., components, which could operate at $\sim 500\,^{\circ}\mathrm{C}$). While the concept of environmentally tolerant technologies is appealing (e.g., removing the need for a pressure vessel and thermal management), actual technology developments may not be able to answer these challenges due to fundamental physical limitations or impractical investment strategies.

6.3. Hybrid systems

In a hybrid architecture, hardened components would be exposed directly to the environment and not-hardened components would be protected. Depending on the mission duration, inside a controlled enclosure, either passive or active cooling could be applied, but only for components that cannot be hardened to tolerate the extreme environments of Venus or Jupiter. Simultaneously, high temperature tolerant components would be employed where practical, including in situ sensors, drills, and sample acquisition mechanisms, which would be fully exposed to the extreme environment.

Consequently, some temperature-sensitive components would be maintained inside an insulated thermal enclosure, while other more tolerant components would remain outside. This approach would result in a simpler and lighter thermal control, and would be more cost-effective. The integration of isolation and tolerance to form a hybrid system is illustrated in Fig. 1.

7. Emerging technologies for extreme environments

Technologies can be categorized as heritage, enhancing, or enabling. Heritage technologies are flight qualified and do not need significant technology investments. Enhancing technologies would benefit the mission, but without them the mission could still be successful, although with a less optimum configuration or reduced utility. Without enabling technologies the mission could not be executed at its conceived way.

In formulating technology roadmaps to handle the extreme environments of these future planetary missions, it is important to understand not only what has been done previously in planetary missions, but also to consider emerging technologies not previously used in space. The emerging technologies have been categorized into three general areas, namely: (a) *environmental protection technologies*; (b) *environmental tolerance for exposed components*; and (c) *robotics in extreme environments*, which includes technologies like mobility or sample acquisition, providing capabilities to operate in extreme environments in order to achieve mission science objectives.

The impact of these new technologies on the Roadmap missions, shown in Table 3, represents an assessment of the potential for further advances in the technologies and their enabling or enhancing effect on the missions. Technology roadmaps have been developed synchronizing the technology development to address these requirements with the milestones of the planned missions. Further details on elements of these three technology areas are given below.

7.1. Protection systems

Protection systems, applicable to each of the discussed environments, were considered. However, the potential of emerging technologies in each area varies, will be discussed below.

7.2. Hypervelocity particle impact

The foam core shield (FCS), designed to shield propellant tanks, also provides a combination of thermal control and hypervelocity impact protection that represents a significant improvement over the use of MLI. Some of the work on penetration codes that has been focused on the space station can be relevant to solar system exploration. Otherwise, there has been limited NASA research specifically focused on the challenges faced in solar system exploration.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in protective systems for hypervelocity particle impacts:

1. new environmental models for meteoroids (data and new models outside/inside 1 AU), cometary, planetary ring, and debris models above 2000 km for the outer planets;

Table 3
Impact of advanced technology development on roadmap missions

Technology areas	Discovery				New frontiers						Flagship (small/large)							
Specific technologies	SB	Moon	Venus	Mercury	NH	Juno	SPABSR	VISE	CSSR	SP	C–H	EE	TE	VME	EAL	NTE	CCSR*	VSSR*
Protection and component hardening																		
High temperature			◐		⊕	⊕		●			⊕			●				●
High pressure			◐		⊕	⊕		●			⊕			●				●
Low temperature	◐	◐		◐	⊕	⊕	◐		◐		⊕		●		●		◐	
Ionizing radiation					⊕	⊕					⊕	◐			●			
Hypervelocity impact			◐	◐	⊕	⊕		◐	◐	◐	⊕	◐	◐	◐	◐	◐	◐	◐
Hypervelocity entry			◐		⊕	⊕	◐	◐	◐	●	⊕		◐	◐		●	◐	●
Robotics																		
High-T aerial mobility			◐		⊕	⊕					⊕			●				●
Low-T aerial mobility					⊕	⊕					⊕		●					
High-T mechanisms			◐		⊕	⊕		◐			⊕			●				●
Low-T mechanisms	◐	◐		◐	⊕	⊕	◐		◐		⊕		◐		●	◐	●	

Convention: ◐ Medium; ● High; ⊕ Ongoing mission or project. SB—small bodies; NH—New Horizons; SPABSR—South Pole-Aitken Basin Sample Return; VISE—Venus In Situ Explorer; CSSR—Comet Surface Sample Return; SP—Saturn Flyby with Shallow Probes; C–H—Cassini–Huygens; EE—Europa Explorer; TE—Titan/Enceladus Exp.; VME—Venus Mobile Exp.; EAL—Europa Astrobiology Lander; NTE—Neptune-Triton Explorer; CCSR—Cryogenic Comet Surface Sample Return; VSSR—Venus Surface Sample Return*—beyond the 5 proposed Flagship missions in the 2006 SSE Roadmap.

2. standardized, validated empirical cratering and penetration models and validated hydrocodes capable of modeling complex shielding geometries for impacts of 5–40 km/s;
3. techniques for rapidly and cheaply testing new shielding configurations for particle masses up to 1 mg and for velocities up to 40 km/s;
4. shielding technologies for light shielding designs for 1 mg particles impacting at 5–40 km/s; and
5. standardized methodology for evaluating the efficiency and reliability of complex shielding schemes.

In addition to preventing spacecraft damage or destruction, accurate environmental impact models, along with valid ground test capabilities, would permit potentially significant savings in mass and mission complexity and possibly increase performance.

7.3. Hypervelocity entry

Most developments in TPS in the last two decades have been targeted at improving the payload fractions. New ablative and reusable materials have been developed and evaluated through arc jet testing. A proposed testing of a number of these materials under the New Millennium program is now on hold. However, the aeroshell for the Mars Science Laboratory mission is being instrumented in order to characterize the entry conditions and entry shell performance.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in TPS for hypervelocity entry:

1. *Thermal protection systems*—The emphasis here must be on dense ablative materials for the environments of the outer planets. Jupiter probes deployed at higher latitudes, such as those envisioned in the Jupiter Flyby with Deep Probes (JFDP), would require TPS mass fractions exceeding 70% with conventional materials. Venus missions requiring entry and sample return missions would also benefit from lowered mass fractions of TPS. The testing of these materials for the outer planets will require major facility investments.
2. *Sensors for aeroshell*—Pressure and temperature sensors are commercially available, but development is needed for measurements of heat flux and recession rates.
3. *Physics-based models*—Although the environment around bodies under benign entry conditions is well understood, extreme environments associated with Jupiter and Saturn probes and a Neptune aerocapture mission are not well demonstrated by the Galileo probe heat shield behavior. The model development must include a strong emphasis on validation.

7.4. High temperatures and pressures

This area has the broadest potential for progress of any of the protection technologies considered in this report. For protection from high pressure, high buckling strength beryllium and titanium matrix materials can enable much lighter pressure vessels that those used previously. Their creep resistance also permits longer-duration missions in the elevated temperature environment at the surface of Venus or for an outer planet deep probe.

For protection from elevated temperatures, a number of different approaches show potential. New insulating materials and architectures for employing those insulating materials have been identified. Phase-change materials offer a mixed prognosis. While there is only limited potential for advances in using the liquid–solid phase transition beyond those achieved with lithium nitrate (195 kJ/kg), a water lithium system exploiting the water-vapor transition with venting to the Venus environment may permit up to 700 kJ/kg. However, these essentially passive or "one-shot" approaches can only prolong surface operations from hours to perhaps days on the surface. For months of operation, a heat pump or refrigerator powered by a radioisotope power system (RPS) will be needed. In order to handle the substantial temperature differentials, efficient mechanical systems will be also required.

The diversity of possible mission architectures dictates that the technology development and design of a pressure vessel for extreme high pressures and temperatures should address both structural and thermal issues. An example of this concept is shown in Fig. 2.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in technologies for high pressure-temperature environments:

1. a pressure vessel with a mass savings of 50–60% compared to a standard monolithic titanium shell;
2. a thermal energy storage system with twice the specific energy capacity of the current state of the art;
3. a thermal energy storage system integrated with the pressure vessel with a tenfold improvement in storage capacity relative to the current phase-change material (PCM) module technology; and
4. a scaleable powered refrigeration/cooling system capable of providing a temperature lift of $\sim 400\,^{\circ}\mathrm{C}$,

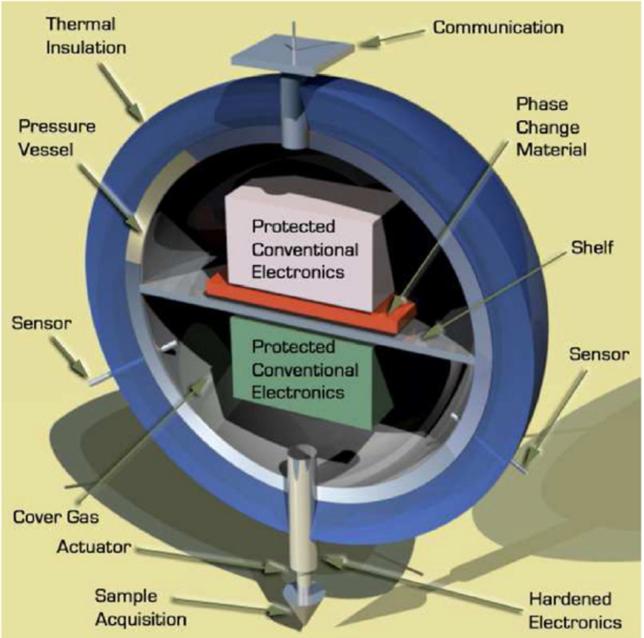

Fig. 2. Illustration of the pressure vessel and thermal management for a Venus in situ mission.

while removing 80 W for a system mass of 60 kg (including an RPS), giving an effective cooling density of about 5 kJ/kg.

7.5. Cold temperatures

Protection against cold-temperature environments involves extension of the WEB technologies used on the MERs. In addition to this purely passive solution, radioisotope heater units (RHUs) may be used to avoid demands on scarce electrical power. For those missions using RPSs, excess (waste) heat from the RPS could provide further protection against the cold environment. Protection from cold environments is not as challenging as protection and isolation from high temperatures.

7.6. Ionizing radiation

Protection from ionizing radiation environments may include shielding by the target body under investigation, shielding by spacecraft systems, such as propellant tanks, as well as dedicated shielding for sensitive components. Recent work has indicated that self-shielding by both Europa and Ganymede is significant and should be accounted for in the design of both orbital and landed missions. There has been a great deal of work on the development of radiation codes, but high-fidelity codes for predicting radiation effects in spacecraft and tests of the effectiveness of different shielding materials are lacking.

Future investments: To meet the needs of future planetary missions, NASA should consider the following investments in ionizing radiation protection technology:

1. establish magnetically trapped charged particle population models, including completing a Jovian model with the remaining Galileo data; revising the Saturn model with Cassini data; developing models for Neptune and Uranus; and modeling the solar charged particle environments near Venus and Mercury;
2. develop shielding effectiveness and spacecraft modeling, including multilayer shielding design guidelines and CAD interface evaluation and development with codes, such as NOVICE or ITS5;
3. conduct ground testing of shielding materials, electron testing of single-layer and multilayer material shielding, and proton testing of single-layer and multilayer material shielding; and
4. validate radiation transport codes and evaluate charged particle adjoint Monte Carlo codes, beginning with ITS5, by comparing outputs of other codes (NOVICE, MCNPX, GEANT4), and ITS5 with ground test results.

The benefits to missions are the reduction in shielding mass required to protect the spacecraft electronics and dielectric materials, as well as increased spacecraft lifetime in severe radiation environments.

7.7. Component hardening

Developing components that can tolerate extreme environments is a complementary approach to protecting the components of a system from the environment. Component hardening is particularly relevant for dealing with environments with extreme temperatures and ionizing radiation effects where complete protection may not be practical for meeting mission objectives.

7.8. High-temperature electronics

NASA has not implemented a mission to a high-temperature solar system environment since the Pioneer Venus and Galileo probes, and neither was equipped with electronic components to tolerate elevated temperatures. However, developments within NASA and the commercial drivers of deep subsurface access have resulted in significant progress on components tolerant of high-temperature environments.

Large-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), as well as vacuum tube active components, have the potential for operating at 500 °C, but so far this potential has only been validated for SiC. A SiC transistor designed and packaged for high temperature has demonstrated 1000 h of operation at 500 °C. In addition to the active devices, passive components (resistors and capacitors) have been demonstrated and progress has been made on development of thermally compatible substrates. A key challenge is the development of interconnects that can survive extended exposure to these temperatures.

On proposed Venus surface missions, high-power electronic and telecommunications systems act as internal heat sources. Placing these systems outside the thermally protected vessel may reduce internal heating and extend the life of the mission. Small-scale integrated SiC, and GaN high-temperature technologies and heterogeneous high-temperature packaging can support this need and provide components for power conversion, electronic drives for actuators, and sensor amplifiers.

Another architectural approach is the use of devices that operate at an intermediate temperature of 300 °C, such as commercially available silicon-on-insulator (SOI) devices. Electronics operating at medium temperatures can reduce the difference between the outside environment and inside the thermally protected system, significantly reducing the associated power requirements for cooling. High-temperature batteries have also demonstrated significant progress and can enable and/or enhance future missions to high-temperature environments.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in high-temperature electronics:

1. High-temperature, long-life (500 h) SiC, GaN, and vacuum tube active components.
2. Small-scale, high-temperature (500 °C) SiC, GaN, and microvacuum device-based integration technology.
3. High-temperature passive components and packaging technology.
4. Device characterization and modeling capability that results in a tools that enables extreme environment electronic design.
5. High-temperature integrated systems.
6. Medium-temperature (300 °C) LSI-scale ultra-low-power SOI CMOS.
7. Integrated medium-temperature electronic systems, such as solid-state recorder, flight microcomputer, and actuator/sensor controller.

7.9. Low-temperature electronics

Developments in cold temperature electronics are currently being sponsored to support the needs of the Mars Science Laboratory and future lunar robotic missions. Commercial development of silicon germanium (SiGe) components is showing a great deal of promise.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in low-temperature electronics:

1. Design methodology for making reliable, ultra-low-power, wide-range low-temperature and low-temperature VLSI class digital and mixed-signal ASICs.
2. Low-temperature and wide-range low-temperature radiation-tolerant, VLSI class, ultra-low-power, long-life Si and silicon-germanium (SiGe)-based electronic components for sensor and avionics systems.
3. Wide-range low-temperature passive components and high-density packaging technology.
4. Research and modeling tools that produce the models that enable low-temperature and wide-range low-temperature radiation-tolerant electronic design.
5. Low-temperature integrated systems, such as solid-state recorder, flight microcomputer, and actuator/sensor controller.

Avionics systems, components (such as sensors, transmitters), and in situ systems (using wheels, drills, and other actuators) that can directly work at cold temperatures (down to −230 °C) will enable the elimination of the WEB and the implementation of distributed architectures that will enable the development of ultra-low-power, efficient and reliable systems.

7.10. Radiation-tolerant electronics

At present the space industry relies on three distinct sources for radiation-tolerant components:

1. *Commercial components*: which are determined to be—perhaps serendipitously—radiation tolerant.
2. *Radiation hard by process* (*RHPB*): which are components manufactured with radiation hardened material processes at specialized foundries.

3. *Radiation hard by design* (*RDBD*): which are components built on commercial lines with commercial materials and processes, but designed to tolerate high radiation doses.

In addition to the DoD developments, NASA has carried out focused investments in rad-hard technology aimed specifically at missions to the Jupiter system under the X-2000 program in the late 1990s, and as part of the Prometheus program between 2002 and 2004. As a result, many components are now available rated at a 1 Mrad total integrated dose (TID), and a broader range of components to 300 krad.

One major gap in the technology has been dense nonvolatile memory (NVM). High-density solid-state recorders (SSRs) used for Earth orbital missions use commercial flash memory devices, which are inherently rad soft. Even massive vaults may not provide the level of shielding needed for operation in the Jupiter system. However, recent progress on chalcogenide random access memory (CRAM) and magnetoresistive memory (MRAM), for which the memory elements are rad hard, may provide a solution.

Future investments: Since this assessment is being superseded by a more comprehensive study conducted in 2007 under the aegis of the Europa Flagship mission study, no specific recommendations are made here. However, NASA will need to initiate a significant effort in this area to evaluate and characterize the options for avionics systems in a methodical fashion. Electro optical components for science instruments will require particular attention since the ability to successfully execute the scientific measurements is inherent to the success of the future missions.

7.11. *High-temperature energy storage*

Primary batteries that release their electrical charge by thermal activation are in routine use on NASA and DoD programs. In the 1970s and 1980s, there was active research on high-temperature rechargeable batteries that operated at 300–600 °C because of the prospects of achieving high energy densities. Progress in lithium-ion technology removed that impetus, but still provided a foundation for several technologies that could be applied in a Venus surface mission, such as an all solid-state battery developed by DoE's Sandia Laboratory for oil drilling applications. Longer-range possibilities include a primary battery concept from JPL using a calcium (Ca) metal anode, nickel-fluoride (NiF_2) cathode, and fluoride-ion based solid-state electrolyte. Not having to cool the batteries will significantly lower the thermal load on a Venus in situ mission, and if the battery can be moved outside the temperature-controlled housing, the size of the enclosure can be reduced.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in high-temperature energy storage:

1. characterize the performance and stability of existing primary batteries at high temperatures (500 °C) and if a promising candidate is found, select it for advanced development;
2. develop an intermediate-temperature secondary battery (250 °C) based on current lithium ion technology; and
3. select the most successful components and create a flight-qualifiable primary and secondary battery for the 250–500 °C temperature range.

7.12. *Low-temperature energy storage*

Storing energy at low temperatures using devices based on chemical energy is challenging since the chemical reactions needed to release electrical energy slow down at low temperatures. There is potential for reducing the operating temperature from the −40 °C achieved in the batteries on the MER mission to perhaps −100 °C. Other chemistries with potential for low-temperature operation are lithium-sulfur and lithium-copper chloride. For energy storage at lower temperatures than −100 °C, other approaches, such as flywheels and superconducting magnetic storage would need to be pursued. However, it is not clear that these approaches would be practical or the needs of Roadmap missions would warrant the investment.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in low-temperature energy storage:

1. Identify electrolytes that have good lithium conductivity at low temperatures.
2. Improve lithium electrode/electrolyte interfacial properties for enhanced charge transfer.
3. Demonstrate technology feasibility with experimental cells at appropriate rates of charge and discharge.

These technologies enable effective operation of rovers/probes/landers in cold environments through mass and volume savings associated with the heavy thermal system that is needed with state-of-practice space batteries and corresponding cost savings.

7.13. Robotic systems

Robotic systems are essential for in situ mission goals to be met and enable the collection and direct examination of samples. Technologies include mechanical systems required for in situ sample acquisition and analysis, as well as aerial mobility systems on Venus or Titan, where atmospheric conditions provide the opportunity for broad survey operations.

7.14. High-temperature mechanisms

Motors and actuators are required for a variety of functions, such as opening and closing valves, deploying landing gear, and operating robotic arms and antenna gimbals. Motors are also required for operating drills, and the acquisition of unweathered samples from at least 20 cm below the surface layer of Venus (e.g., for the VISE mission). For VME, motors and actuators will be also needed for the mobility systems and will require reliable operations for at least hundreds of hours.

Standard actuators based on ferromagnetic or ferroelectric materials face an intrinsic challenge at high temperatures since at the Curie temperature the phase transition causes them to lose their actuation capability. In response to this need, NASA has sponsored the industry development of a switched reluctance motor, which operates without permanent magnets and it has been successfully tested at 460 °C. No other motors are currently known that could operate under Venus conditions for any significant period of time.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in high-temperature mechanisms:

1. develop a sample acquisition system operable at 500 °C;
2. develop mechanisms associated with aerial mobility; and
3. provide for extended operations for tens of hours.

7.15. Low-temperature mechanisms

Cold-temperature mechanisms are needed to provide many of the same functions identified for the hot mechanisms discussed above. Low-temperature motors and actuators are needed for the Titan Explorer, for rovers associated with the Lunar Aitken Basin mission, and for the EAL. The motors are needed for sample acquisition systems, mobility systems, robotic arms, and other applications.

Current operation of gears bearings and lubricants at −130 °C is limited to 1,000,000 cycles, while drive and position sensors are also limited to operation at −130 °C.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in low-temperature mechanisms:

1. an integrated wheel/ballute motor, with appropriate lubrication, capable of operation down to −180 °C and 50,000 revolutions;
2. a low-temperature robotic arm for sample acquisition; and
3. integration with technologies hardened to 1000 krad of radiation.

7.16. High-temperature mobility

High-temperature mobility systems are needed for future missions to the surface and lower atmosphere of Venus. For a Venus Surface Sample Return (VSSR) mission, it is necessary to raise samples from the surface to altitudes of 50–60 km. Efforts to develop a single stage polymer balloon for this application have been unsuccessful, however, a two stage balloon with a metal bellows first stage appears practical. The metal bellows approach has been tested at Venus temperatures. The metal bellows technology also appears to be applicable to the proposed VME mission and would easily permit operations over an altitude range of 10 km.

Future investments: To meet the needs of Roadmap missions, NASA should consider the following investments in high-temperature mobility systems:

1. Large-diameter bellows balloon design, fabrication, and testing.
2. Deployment and inflation design, fabrication, and testing.
3. System integration and testing.

7.17. Low-temperature mobility

Low-temperature mobility systems are primarily needed for the Titan Explorer mission. There has been significant progress over the last several years in aerial mobility systems. Balloon envelope materials have been developed that can tolerate Titan temperatures and various architectures for controlled mobility have been investigated. A thermal Montgolfière balloon capable of multiyear operation looks particularly attractive, although it has not yet been demonstrated in a relevant environment. Autonomous control systems capable of responding to unpredictable conditions in the environment have also been evaluated.

Future investments: To meet the needs of Roadmap missions, NASA should consider investments in low-temperature mobility to mature the technology to the point that it can be adopted for the Titan Explorer mission. This technology has several sub-components including cryogenic balloon materials, balloon fabrication, aerial deployment and inflation, aerobot autonomy, and surface sample acquisition and handling. The technology needs are currently being updated in a NASA sponsored flagship class mission study in order to define the technology needs for a Titan Explorer mission.

8. Summary

Most planetary exploration targets of interest present multiple environmental challenges, requiring the development of technologies designed for multiple environmental extremes. In general, there may be several architectural approaches for coping with these environments, some involving protection, others environmental tolerance or a combination of both. Systems analyses and architectural trades will be needed to develop specific performance targets for the different technologies and to establish priorities in the technology investment program.

Over the first decade, a number of technologies are needed to enable proposed planetary exploration missions. These include: radiation-hard electronics for missions to the intense radiation environments of the Jupiter system; entry probe technology that could enable atmospheric entry into Saturn and Jupiter, and for operation down to 100 bar pressure depth; technologies for (short-duration) survival, operation, and sample acquisition on the surface of Venus; and drilling, sample manipulation, and storage at cryogenic temperatures for comet missions.

For the subsequent decade, the NRC DS report [1] and the SSE Roadmap [3] identified the need for technologies to enable aerial vehicles for the exploration of Venus, Mars, and Titan; and long-lived high-temperature and high-pressure systems for operation on and near the surface of Venus.

Since planetary extreme environments and related technologies are unique to space agency driven missions, agencies are expected to take the lead in the development of these critical technologies, with support from industry and academia.

Acknowledgments

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. The authors of this paper wish to thank the Extreme Environments Study Team members at JPL, including: Ram Manvi, Gaj Birur, Mohammad Mojarradi, Gary Bolotin, Alina Moussessian, Eric Brandon, Jagdish Patel, Linda Del Castillo, Michael Pauken, Henry Garrett, Jeffery Hall, Rao Surampudi, Michael Johnson, Harald Schone, Jack Jones, Jay Whitacre, Insoo Jun—in addition to the authors of this paper: Tibor Balint, Elizabeth Kolawa (study lead), James Cutts and Craig Peterson. Team members from other NASA centers included: Ed Martinez, Raj Venkapathy, and Bernard Laub from NASA-Ames Research Center; and Phil Neudeck from NASA-Glenn Research Center. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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